Sterile neutrinos: a subjective review

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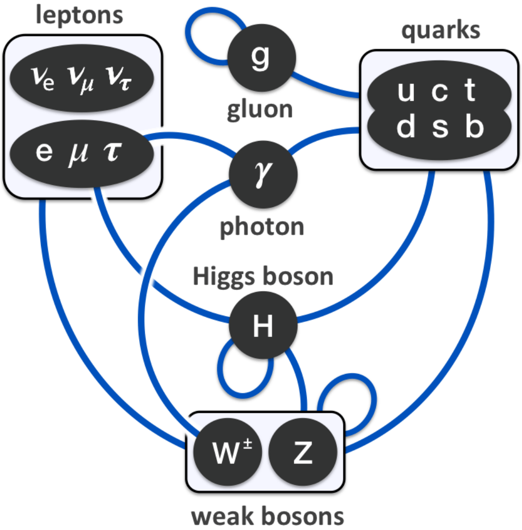
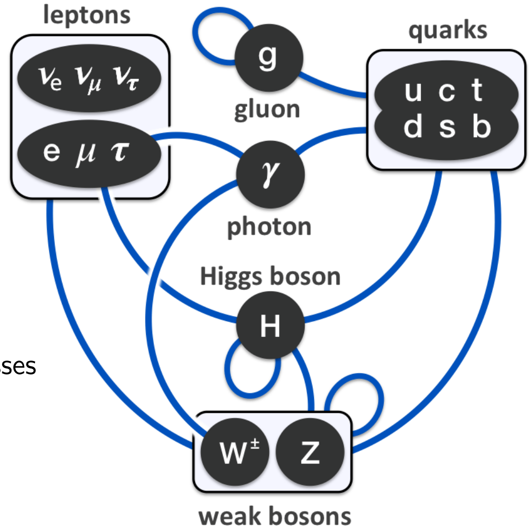
Outline of talk

The SM is a triumph



The SM is a triumph ... and yet BSM exists



Neutrino masses

Gravity

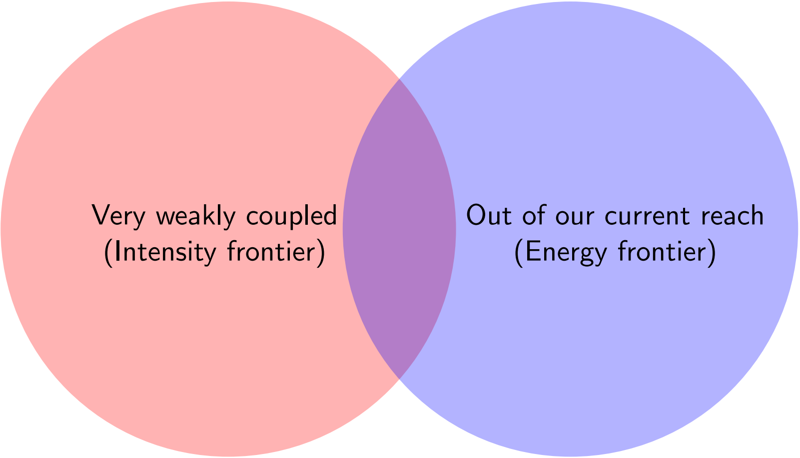
Dark matter

Naturalness?

Strong CP?

Flavour?

But where is it?



Lagrangian with a singlet fermion

We introduce $N_i \sim (1, 1, 0)$ with $i \in [1, n]$,

$$\mathcal{L} = \mathcal{L}_{\mathsf{SM}} + \frac{1}{2}\overline{N}_i i\partial\!\!\!/ N_i \underbrace{+ \frac{M_{ij}}{2}\overline{N_i^{\mathsf{c}}}N_j}_{\text{Majorana mass}} \underbrace{+ y_{\alpha i}\overline{L}_\alpha \widetilde{H} N_i + y_{\alpha i}^* \overline{N}_i \widetilde{H}^* L_\alpha}_{Q \text{ doublet-like Yukawa terms}}$$

Mass term

Could lead to lepton number violation (and $B - L$) at tree-level.

Allows *e.g.* $0\nu\beta\beta$ decay, or same-sign dilepton signatures.

Yukawa term

Dirac mass terms coupling ν_{L} to N.

Below EW: mass mixing effects leading to weaker-than-weak interactions between N and SM.

Neutrino mass

Below EW scale, we find an (extended) neutrino mass matrix

$$m = \begin{pmatrix} 0 & y^{\mathsf{T}} v \\ yv & M \end{pmatrix}$$

Dirac masses

$M = 0$ but $y \neq 0$

$m_\nu = yv$

Pseudo-Dirac

$M \ll y \neq 0$

$m_\nu \approx yv$

Type I see-saw

GUT$\sim M \gg y$

$m_\nu \approx v^2 \frac{y^{\mathsf{T}} y}{M}$

Low-scale see-saw

TeV$\sim M \gg y$

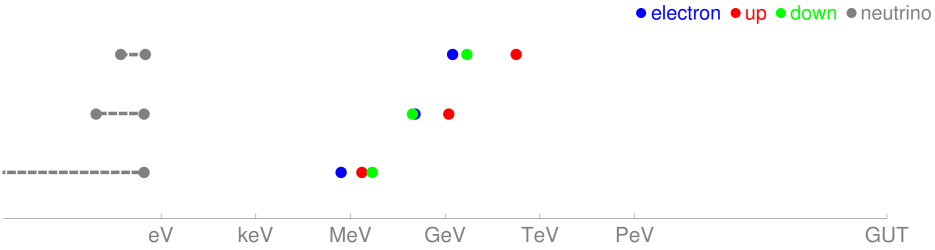
$m_\nu \approx v^2 \frac{y^{\mathsf{T}} y}{M}$

Inverse, linear, extended, double...

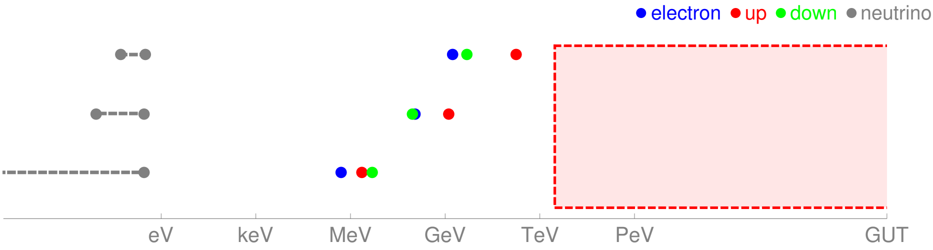
Outline of talk

1. How to extend the SM?
2. Overview of sterile phenomenology
3. MeV scale decays
4. Conclusions

Scales for sterile neutrinos



Scales for sterile neutrinos



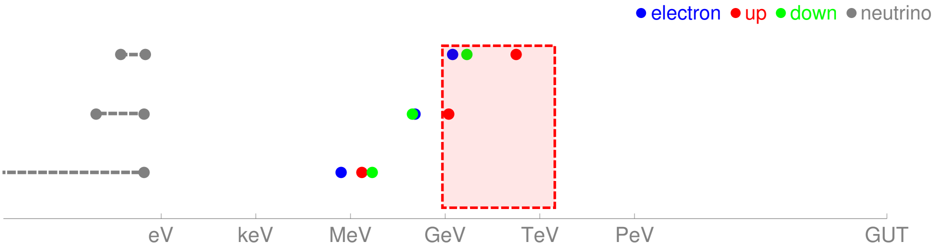
Phenomenology

- Future colliders (at the lowest scale)
- Model related processes *e.g.* proton decay
- Leptogenesis

Models

- (Normal) Type I see-saw

Scales for sterile neutrinos



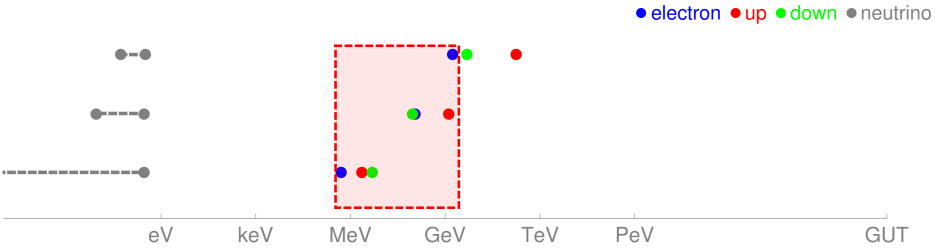
Phenomenology

- Direct production from D mesons (SHiP), at colliders
- charged Lepton Flavour Violation, LNV at colliders

Models

- Low-scale Type I see-saw
- Inverse see-saw, extended see-saw

Scales for sterile neutrinos



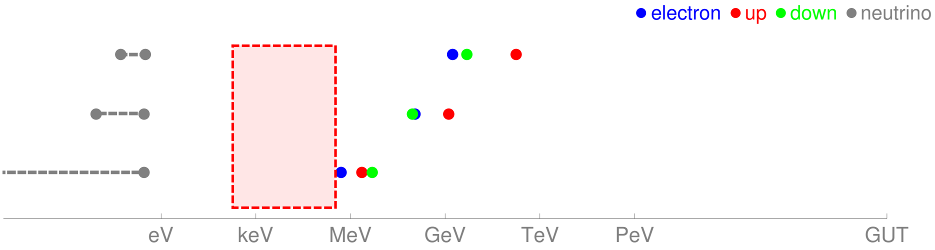
Phenomenology

- Beam dump searches, light meson decay, peak searches
- Electroweak constraints, BBN, $0\nu\beta\beta$

Models

- Small couplings low-scale Type I see-saw
- Marginally unnatural inverse see-saw

Scales for sterile neutrinos



Phenomenology

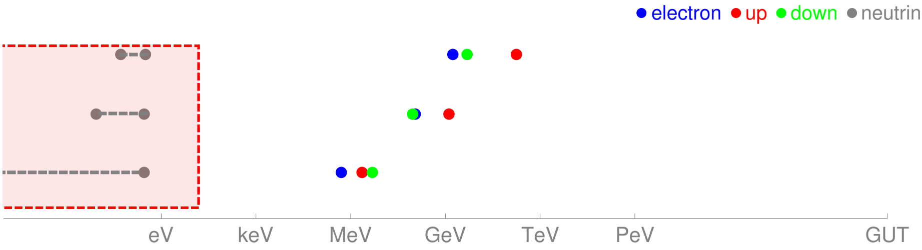
- keV dark matter, emission lines
- Kinks in β-decay spectrum, peak searches, $0\nu\beta\beta$

Models

- Symmetries, or radiative mechanisms for keV DM.
- Suppressed couplings low-scale see-saw models

See keV whitepaper 1602.04816

Scales for sterile neutrinos



Phenomenology

- eV anomalies
- Oscillations (SBL, atmospherics, reactors ...)
- Cosmology – $\sum_i m_i$, N_{eff}, BBN

Models

- Many mechanisms, but require suppressed couplings/fine tuning.

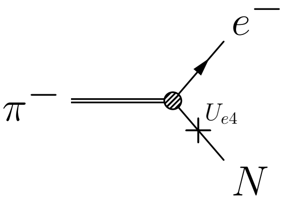
Outline of talk

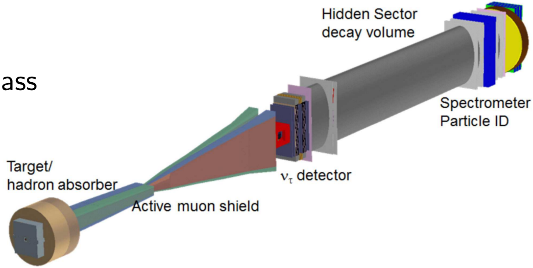
Direct production of N

- Meson decay (π, K, D) can produce steriles via mixing (when kinematically allowed)

- Beam dump-style experiments can use this to search for N

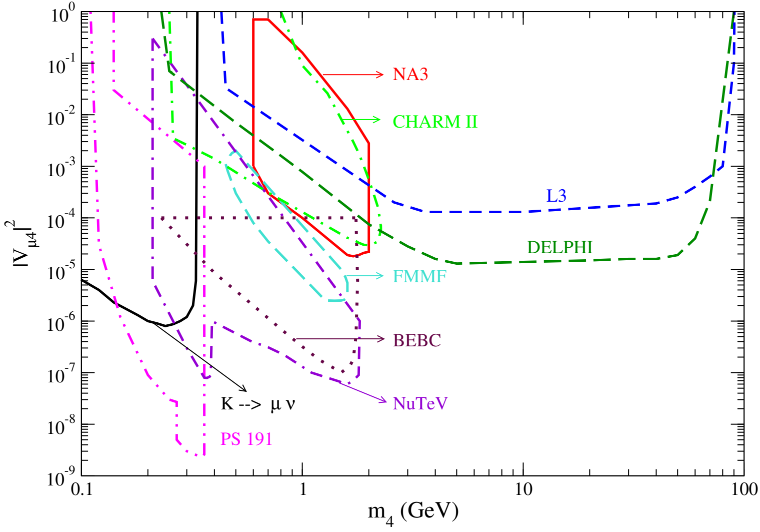
- They place some of the strictest bounds in this mass range





Schematic of the SHiP experiment from 1504.04956.

Existing bounds



Atre, Han, Pascoli and Zhang, *JHEP 0905:030*, (2009) Conventional neutrino beams should also see sterile decay events.

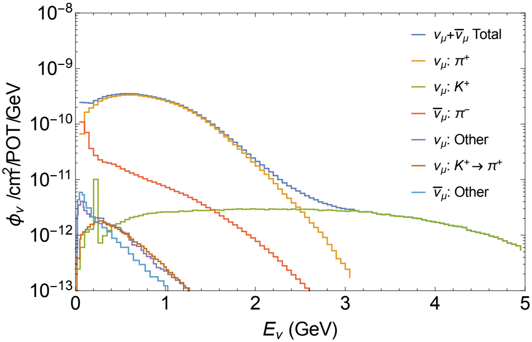
Asaka, Eijiama and Watanabe *hep-ph/1212.1062*

	PS191 [19]	T2K [23]	MINOS [24]	MiniBooNE [25]	SciBooNE [26]
POT	0.86×10^{19}	10^{21}	10^{21}	10^{21}	10^{21}
$(\text{Distance})^{-2}$	$(128\,\text{m})^{-2}$	$(280\,\text{m})^{-2}$	$(1\,\text{km})^{-2}$	$(541\,\text{m})^{-2}$	$(100\,\text{m})^{-2}$
Volume	$216\,\text{m}^3$	$88\,\text{m}^3$	$303\,\text{m}^3$	$524\,\text{m}^3$	$15.3\,\text{m}^3$
Events	1	9.9	2.7	15.8	13.5

- To first approximation, fluxes scale by U^2

$$\phi_N(E) \approx |U_{e4}|^2 \, \phi_\nu(E)$$

- Kinematic differences
- Decay in flight enhances lower-energies



Neutrino fluxes by parent decay at microBooNE.

Heavy neutrinos at oscillation experiments

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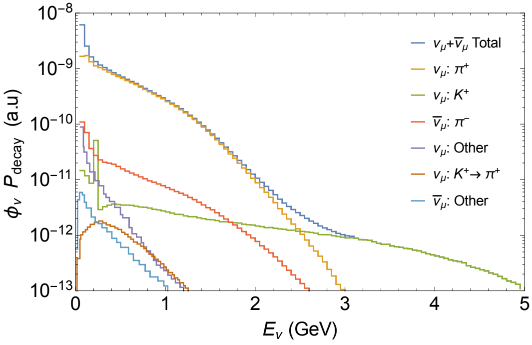
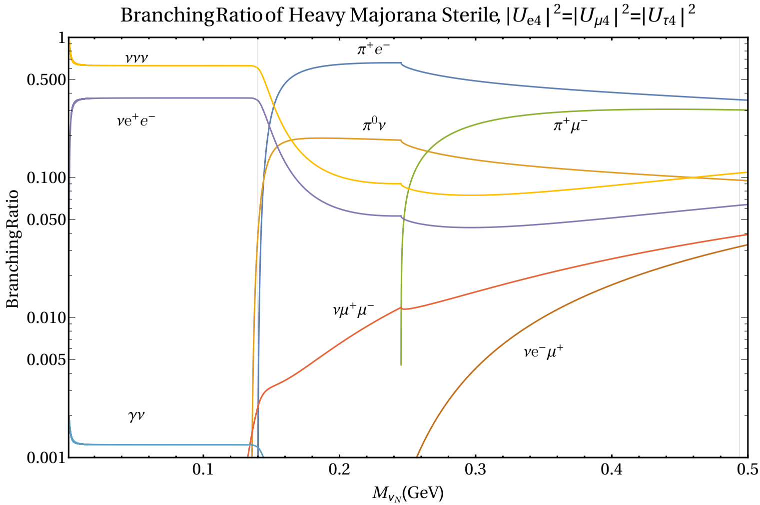


Neutrino fluxes by parent decay at microBooNE.

Decay signatures

Visible decays (in minimal model) into dileptons and lepton+pion.



PB, S.Pascoli, M.Ross-Lonergan, *in preparation*

Short Baseline Neutrinos @ Fermilab

See SBN proposal *1503.01520*

- Three detectors: SBND (LAr1-ND) (110 m), MicroBooNE (470 m) and ICARUS-T600 (600 m).
- Operating the same technology: Liquid Argon Time Projection Chambers (LAr-TPC)
- Rich physics program: sterile oscillations, neutrino cross-sections on Ar, ...

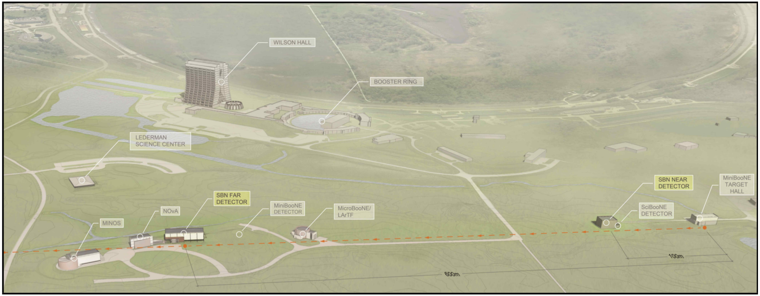
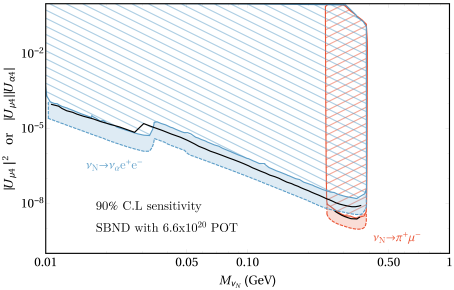
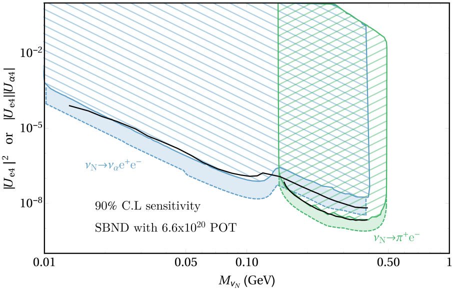
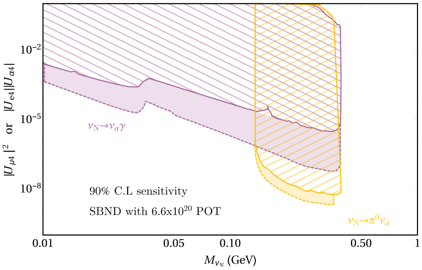


Figure reproduced from SBN Proposal *1503.01520*

SBN @ Fermilab: constraints



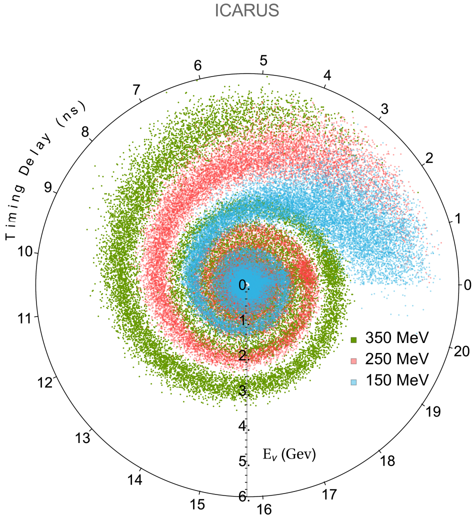




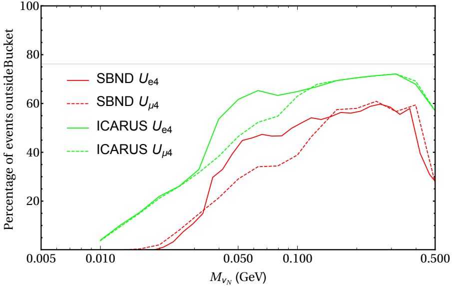
- SBND could extend current bounds on $\nu e^+ e^-$ and $l^\pm \pi^\mp$ by a $\sim \times 10$.
- Channels such as $\pi^0 \nu$ and $\nu\gamma$, can be bounded for the first time by beam dump experiments.

PB, S.Pascoli, M.Ross-Lonergan, *in preparation*

SBN @ Fermilab: timing



- Heavy propagating degrees of freedom produce timing effects.
- A clear signal of heavy particle decay!



PB, S.Pascoli, M.Ross-Lonergan, *in preparation*

Outline of talk

Conclusions

- Sterile fermions are a plausible part of the true BSM model.
- They are naturally associated with the neutrino sector. But their full parameter space is enormous, connecting them to many different phenomena.
- Decaying sterile fermions can be searched for in beam dump experiments as well as conventional neutrino beams.
- We have assessed the potential of SBN for this search: it can improve current bounds and use excellent particle reconstruction to search for difficult channels. It could also see a distinctive timing effect.

Thank you for listening!